

# **The Behaviour Of Vertical Jet Fires Under Sonic And Subsonic Regimes**

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Accidental release scenarios such as flammable gas leaks or ruptures of pipes and pressurised process-equipment normally originate high velocity jets which, if ignited, give rise to jet fires. Although the direct effects of jet fires are considered to be relatively smaller than that associated to other types of fires, they are characterized by high heat fluxes and, especially if there is flame impingement, they can originate a domino effect, leading to a larger accident. A recent historical analysis has shown that in approximately 50% of the jet fire events registered in accident data bases another event with severe effects is originated. Nevertheless, jet fires are not well known, since most of the experimental work concerns small jet fires (up to 2.5 m in length), subsonic flames or flares. This communication presents the analysis of the measurements performed on relatively large-scale turbulent vertical jet diffusion flames of propane in still air (flame lengths of up to 10 m). The test conditions analyzed covered sonic and subsonic flows, the use of six different-sized interchangeable nozzles, three heat flow sensors located at different radial distances from the flame axis and the use of thermographic and video cameras, which images were used to determine the length and shape of jet fires. The results obtained show the flame length to increase with the orifice diameter and the fuel mass flow rate. The flame length under sonic and subsonic regimes can be predicted as a function of Reynolds number (Eq. (1)). The shape of the present vertical sonic and subsonic jet flames seems to correspond to a cylinder. The thermal radiation intensity ( $I$ ) from jet fires decreases as the heat flow sensors' radial distance from the flame axis increases and increases with the mass flow rate.

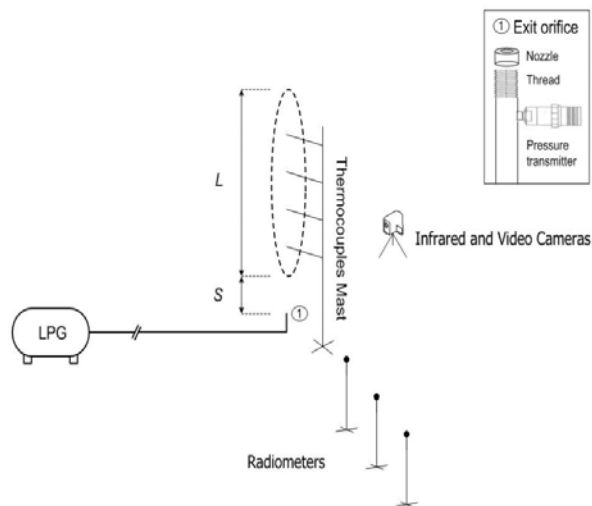
## **1. Introduction**

Although jet fires have a relatively shorter distance of influence than that associated to other major accidents that can take place in processing plants or in the transportation of hazardous materials, they are of particular interest, since they can frequently be considered as the first stage of subsequent major accidents, due to their effects on the near-by equipment through flame impingement and heat radiation. This is known as a domino effect. A recent historical analysis has shown that one of two jet fire events registered in accident data bases originated a secondary accident, generally an explosion (Gómez-Mares et al., 2008). Although several expressions have been suggested to estimate the probable jet fire size, most of them have been obtained through

experimental studies concerning laboratory small-scale flames or subsonic jet flames (Hawthorne et al., 1949; Schuller, 1983; Kalghatgi, 1984; Sonju and Hustad, 1984; McCaffrey, 1989; Rokee et al., 1994; Santos and Costa, 2005; Kiran and Mishra, 2007). However, these conditions significantly differ from those found in real accidental jet fires, as the flames are much larger and the jet usually exits at sonic velocity. In this communication, the experimental measurements (i.e. flame length, shape and thermal radiation intensity) performed on vertical jet fires of propane issuing into still air, with flame lengths up to 10 m at sonic and subsonic regimes are presented.

## 2. Experimental method

Turbulent vertical jet diffusion flames of propane issuing into still air have been obtained with sonic and subsonic flows during field tests. Release interchangeable circular nozzles diameters were between 10 and 43.1 mm (the last orifice diameter represented the full rupture of the pipeline), resulting in observed flames lengths up to 10 m. The pressure at 0.05 m upstream the release point was measured using an electronic pressure transmitter; this was taken to be the upstream stagnation pressure of the flow. The static pressure at the outlet orifice, the jet velocity at the outlet orifice, and the mass flow rate for both sonic and subsonic regimes, were calculated by applying the appropriate thermodynamic relations. The use of thermographic and video cameras let the flame length and shape to be determined. The thermal radiation intensity from jet fires was also measured through three heat flow sensors located at 1 m, 3 m and 5 m from the flame axis, respectively. When the 15 mm outlet orifice diameter was employed, the heat flow sensors were located at 3 m, 5 m and 10 m, respectively. A schematic of the experimental set-up is shown in Fig. 1.



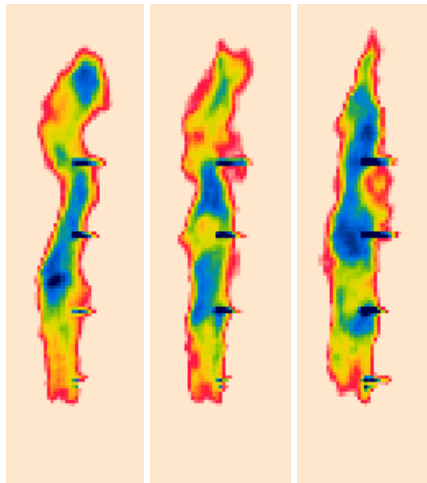
*Fig.1. Schematic diagram of experimental set-up.*

### 3. Flame length and shape

For each operating condition, infrared and visible images of the flame were taken with exposure times of four and 25 images per second, respectively. The flame length ( $L$ ), defined as the distance from the base of the lifted flame to the flame tip, and flame shape were obtained from the analysis of each visible and infrared image, corresponding to the stationary state, using a criterion of temperature. After testing several different temperatures, a temperature of 800 K was selected to define the jet flame surface in the infrared images. At this temperature, both the visible and infrared jet flame images overlapped with a fairly good agreement.

#### 3.1 Flame shape

The shape of jet flames is affected by diverse factors, such as the fuel release orientation and the presence or absence of wind during the attainment of flames. Concerning vertical flames, several studies have suggested different shapes to define the visible jet flame form. Some of them have suggested a cylindrical shape, based on theoretical and experimental studies on subsonic jet flames (Schuller, 1983; Sonju and Hustad, 1984; Hustad and Sonju, 1986; Bagster and Schubach, 1996); other authors have proposed a figure similar to a frustum of a cone (Gollahalli et al., 1975; Kalghatgi, 1983; Chamberlain, 1987), however, although this last shape can represent the form of turbulent diffusion flames in a cross-wind or flares under the influence of wind fairly accurately, it does not correspond to the shape of a real accidental jet fire in still air. In fact, through the analysis of both visible and infrared images, the shape of the present vertical jet flames could be approximated to the previously suggested cylindrical shape (Fig. 2) (Schuller, 1983; Sonju and Hustad, 1984; Hustad and Sonju, 1986; Bagster and Schubach, 1996).



*Fig. 2. Successive images of jet flames issuing from a 12.75 mm outlet orifice diameter. A temperature of 800 K defines the jet flame contour. The time interval between the successive images is 0.25 s. The height at which the outlet orifice diameter ( $d$ ) was located coincides with the bottom of each figure.*

### 3.2 Flame length

The flame length ( $L$ ) was found to be a function of the mass flow rate ( $m$ ) (Fig. 3). Although the dependence on the orifice exit diameter ( $d$ ) is hidden in this kind of log-log plot (except for the data corresponding to  $d = 43.1$  mm, which show a light different trend), it was found that  $L$  depends on both variables, increasing with  $m$  and  $d$  (Palacios et al., 2009). This had been already noticed by Kalghatgi (1984), with subsonic hydrocarbon jet flames and sonic hydrogen jet flames up to 2 m in length.

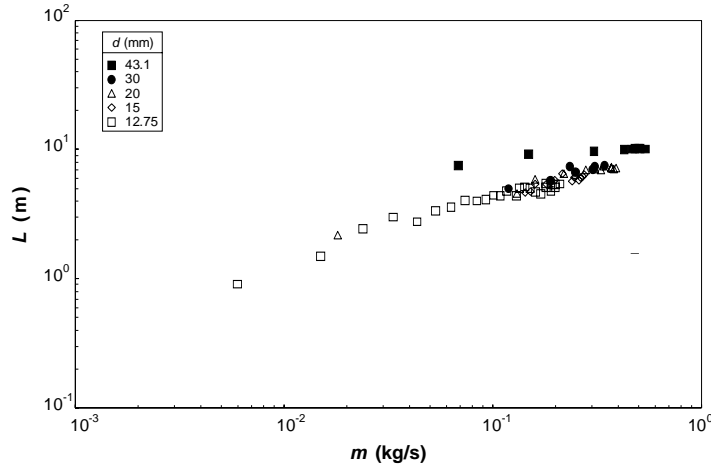


Fig 3. Variation in the sonic and subsonic propane flame lengths ( $L$ ) as a function of fuel mass flow rate ( $m$ ), for various orifice outlet diameters ( $d$ ).

The non-dimensional flame length ( $L/d$ ) was also correlated as a function of the Reynolds number ( $Re$ ).  $L/d$  was found to scale approximately with the 0.27 power of  $Re$  (Eq. 1), showing again flame length dependence on both variables: mass flow rate and orifice exit diameter.

$$L/d = 6.73 \cdot Re^{0.27} \quad (1)$$

## 4. Radiation

The thermal radiation intensity from jet flames was measured by using three heat flow sensors located at different radial distances from the flame axis. The distances were 1 m, 3 m and 5 m, respectively, except for the 15 mm outlet orifice diameter, where the heat flow sensors were located at 3 m, 5 m and 10 m, respectively.

Fig. 4 shows the variation of  $I$  from jet fires issuing through a 15 mm orifice exit diameter as a function of the distance. The results show that as the distance increases,  $I$  decreases. This is due to the absorption of radiant heat by the atmosphere and to the variation of the view factor. From Fig. 4 it can also be seen that for a given distance,  $I$

increases with the mass flow rate ( $m$ ). Similar results were obtained with the other circular nozzles.

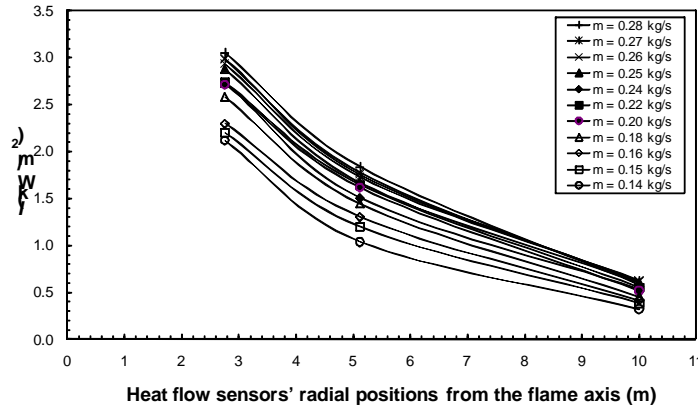


Fig. 4. Variation of the thermal radiation intensity ( $I$ ) as a function of the distance from the flame axis, for a 15 mm orifice outlet diameter.

## 5. Conclusions

Jet fires can originate domino effect essentially when there is flame impingement on some equipment. To foresee this, the prediction of length and shape of jet fires is essential. Although several expressions have been suggested for predicting the flames size, most of them are based on experimental work concerning small-scale jet fires or subsonic flow, while in practice a real accidental jet fire will be probably sonic. The experimental data obtained with vertical sonic and subsonic jet fires of propane up to 10 m in length, have shown that the flame length increases with the orifice diameter and the fuel mass flow rate. An expression, Eq. (1), has been suggested for predicting the flame length under sonic and subsonic regimes, as a function of Reynolds number. The shape of vertical sonic and subsonic jet flames in still air can be approximated to a cylinder. As for the thermal radiation intensity ( $I$ ) arising from propane jet fires, it has been shown that it decreases as the distance from the flame increases, and it increases with the mass flow rate.

## Nomenclature

$d$	orifice or outlet diameter (m) [mm]
$I$	incident radiation heat ( $\text{kW}/\text{m}^2$ )
$L$	flame length, from the base of the lifted flame to the flame tip (m)
$m$	fuel mass flow rate ( $\text{kg}/\text{s}$ )
$Re$	Reynolds number ( $d \cdot V \cdot \rho / \mu$ ) (-)
$S$	lift-off distance (m)
$V$	velocity in the jet at the gas outlet ( $\text{m}/\text{s}$ )
$\mu$	dynamic viscosity at the outlet orifice ( $\text{kg}/\text{m} \cdot \text{s}$ )
$\rho$	density at the outlet orifice ( $\text{kg}/\text{m}^3$ )

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